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Optical Waveform Sampling and Error-free Demultiplexing of 1.28 Tbit/s Serial Data in a Silicon Nanowire

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Abstract: We experimentally demonstrate 640 Gbit/s and 1.28 Tbit/s serial data optical waveform sampling and 640-to-10 Gbit/s and 1.28 Tbit/s-to-10 Gbit/s error-free demultiplexing using four-wave mixing in a 300nm×450nm×5mm silicon nanowire.

OCIS codes: (190.4360) Nonlinear optics, devices; (060.2330) Fiber optics communications

1. Introduction

Optical signal processing in pure silicon has gained considerable interest in the last five years, with pioneering work presented in e.g. [1] followed by very recent high-speed advances such as 160 Gbit/s demultiplexing [2] and wavelength conversion [3]. Using pure silicon for optical processing has a huge potential, as it is CMOS compatible and allows for future seamless integration with electronics, and thus paves the way for advanced optical chips. The key to using silicon for optical processing is nano-engineering of the waveguide to promote the desired optical effect for switching (e.g. optimize the dispersion to enhance four wave mixing (FWM)) over the often detrimental two-photon absorption (TPA). We have very recently discovered that a Si nanowire response is not limited to a few hundred Gbit/s, but can be extended to beyond 1 Tbit/s, and here we present the first optical signal processing results on a data signal at the record-high bit rate of 1.28 Tbit/s.

In this paper, we experimentally demonstrate two types of Tbit/s optical signal processing, optical waveform sampling and error-free demultiplexing of a 1.28 Tbit/s serial data signal by FWM in a Si nanowire only 5 mm long.

2. Experimental setup

Figure 1 (a) shows the experimental set-up and premises for the Tbit/s demonstration.

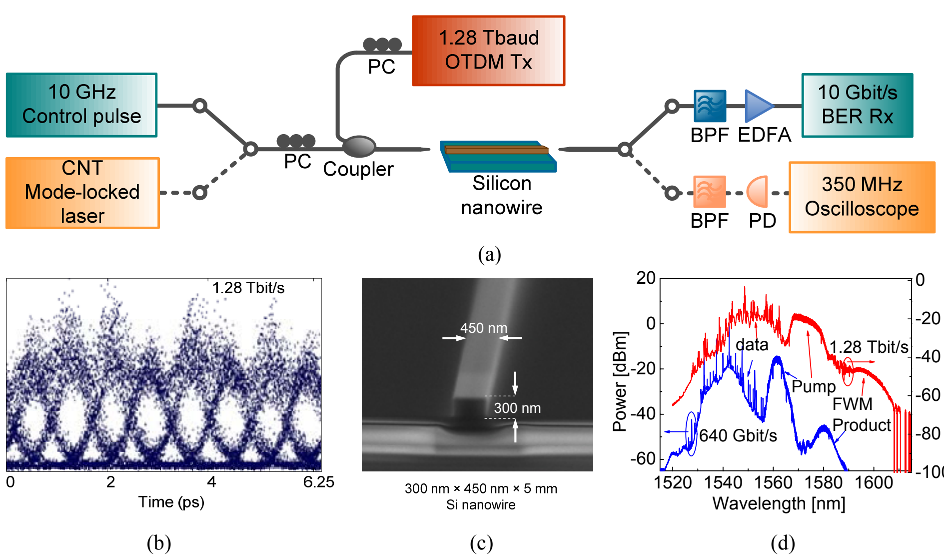

Figure 1. (a) Experimental set-up. A 1.28 Tbit/s serial data signal [4] is injected into the silicon nanowire along with control pulses, either at 10 GHz for demultiplexing or at 16.8 MHz (CNT laser) for optical sampling. (b) Eye-diagram of the generated 1.28 Tbit/s data signal measured by a commercial sampling oscilloscope. (c) Scanning electron micrograph of the 300 nm × 450 nm ×5 mm Si nanowire used in the experiment. (d) Optical output spectra from the Si nanowire for 640 Gbit/s and 1.28 Tbit/s, respectively.

The 1.28 Tbit/s data signal is generated in an optical time division multiplexing (OTDM) transmitter [4], which is polarization and PRBS preserving (for PRBS 2^7-1). The bit rate is adjustable, so characterizations are conducted at

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both the moderate bit rate of 640 Gbit/s, and at the record-high 1.28 Tbit/s. For 1.28 Tbit/s, though, the pulses are compressed to 330 fs FWHM while for 640 Gbit/s they are 500 fs FWHM. This gives rise to a wider data spectrum at 1.28 Tbit/s, and so the wavelength separation between control and data must also be larger. The data signal is injected into the Si nanowire together with control pulses. The set-up allows for flexible switching between control pulse sources, to provide demultiplexing or optical sampling. For demultiplexing, a 10 GHz control pulse source is used [4], and for sampling, a 16.8 MHz repetition rate free-running mode-locked fiber laser, using carbon nanotubes (CNTs) as mode-locker [5] is used. The demultiplexing control pulse width is 440 fs (for 1.28 Tbit/s and 1.2 ps for 640 Gbit/s) and the sampling pulse width is ~ 750 fs. Optimum FWM between control and data pulses is ensured by careful polarization alignment into the Si nanowire. The FWM product is filtered out and for the demultiplexed data received in a bit error rate receiver, and for the sampling received in a high sensitivity photo detector (200 MHz bandwidth) directly connected to a 1Gsample/s oscilloscope. Figure 1 (b) shows the eye-diagram of the 1.28 Tbit/s data measured using a commercial sampling oscilloscope. The data pulses are only 330 fs wide, but appear broadened in the eye-diagram due to the limited time resolution of the commercial sampling oscilloscope.

The silicon nanowire used in these experiments is 5 mm long and its cross-section dimensions are 300 nm × 450 nm, Figure 1 (c). Nano-taper couplers [6] are used at both ends of the waveguide to increase fiber-to-chip coupling efficiency. The insertion loss of the silicon nanowire is 7.5 dB, including 2.5 dB propagation loss and 5 dB coupling loss. For the full sampling set-up, the fiber-to-fiber conversion efficiency becomes -12.5 dB, when accounting for the duty cycle of the pump, and for the full demultiplexing set-up -20.5 dB.

To evaluate the speed potential of the Si nanowire, it is first subjected to detailed characterizations at 640 Gbit/s and subsequently thorough demonstrations at 1.28 Tbit/s.

3. 640 Gbit/s characterization of sampling and demultiplexing

The 640 Gbit/s results are shown in Figure 2. The data signal central wavelength is at 1545 nm and the sampling pulses are at 1565nm. The average power of data signal and sampling pulses sent into the silicon nanowire are 20 dBm and -9.7 dBm, respectively. The FWM product is filtered out at 1586 nm and directly detected. Clear eye-diagrams are observed on the oscilloscope when correcting for the frequency offset between data and sampling pulses by fine adjusting the repetition rate of the sampling laser. The 500 fs pulses (measured by an autocorrelator) are seen in the 1.56 ps time slot without overlap between neighbouring pulses and with minimal broadening to only 560 fs.

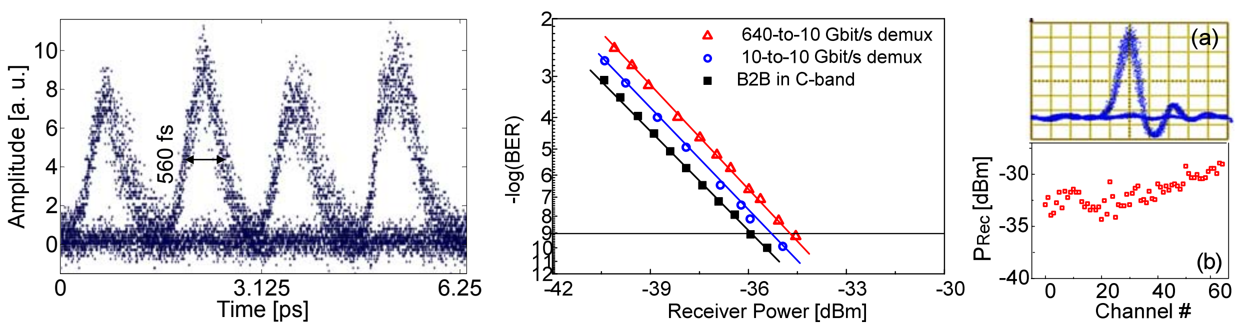

Figure 2. (Left) Clear eye-diagram from Si-based optical sampling. (Middle) BER performance of 640-to-10 Gbit/s demultiplexing. (Right. a) demuxed eye-diagram. (Right. b) receiver sensitivity at BER 10^{-9} for all 64 channels confirming error free operation.

In the demultiplexing experiment, the 10 GHz control pulse train with central wavelength at 1561 nm and 14 dBm average power is coupled into the silicon nanowire as the pump signal. The FWM product is filtered out and sent into an L-band receiver. The bit-error-rate (BER) performances of 640-to-10 Gbit/s demultiplexing are measured and shown in Figure 2 (Middle). Error-free operation with no error floor down to a BER of below 10^{-9} is achieved at -34.4 dBm, with only 1.3 dB penalty compared to the C-band 10 Gbit/s reference. This 1.3 dB penalty includes the full system penalty including the difference between the C- and L-band receivers. A B2B in the L-band is measured as a 10-to-10 Gbit/s demultiplexing, converting the 10 Gbit/s signal from C-band to L-band. Compared to this L-band 10 Gbit/s reference, the 640-to-10 Gbit/s demultiplexing only has 0.6 dB penalty at error free operation. Figure 2 (Right. a) shows a clear eye-diagram of a 640-to-10 Gbit/s demultiplexed channel. Figure 2 (Right. b) shows the measured receiver sensitivity for all 64 OTDM channels. All 64 channels are error-free with an average receiver power at BER of 10^{-9} of -31.8 dBm, with a ~5 dB variation among the channels.

4. 1.28 Tbit/s demonstration of sampling and demultiplexing

In this section we present the first 1.28 Tbit/s signal switching demonstration in a silicon nanowire. Since the optical spectrum of the 1.28 Tbit/s signal is broader than at 640 Gbit/s, due to further temporal pulse compression, the signal central wavelength is tuned to 1551 nm to fit the whole spectrum in the C-band. Accordingly, the sampling pulse and the 10 GHz control pulse wavelengths are shifted to about 1574 nm. Sampling the waveform, results in the 1.28 Tbit/s open eye-diagrams shown in Figure 3 (left). Compared to the sampled eye-diagram from the commercial sampling system shown in Figure 1, the timing resolution is clearly better. In the Si nanowire sampling system, the ~330 fs pulses, though broadened to 510 fs during the sampling process, are clearly distinguished in each of the 780 fs 1.28 Tbit/s time slots. This is the first sampling result where the individual pulses of a Tbaud signal are clearly separated.

In the 1.28 Tbit/s-to-10 Gbit/s demultiplexing, error free operation is achieved at -27.3 dBm sensitivity with no sign of an error floor, thus clearly demonstrating the Tbit/s capabilities of the Si nanowire platform. There is a 6.7 dB penalty compared to the L-band 10 Gbit/s reference. This higher penalty compared to the 640 Gbit/s demultiplexing is expected to be caused by a lower FWM conversion efficiency for the 1.28 Tbit/s set-up, due to the longer spectral distance between the pump and signal.

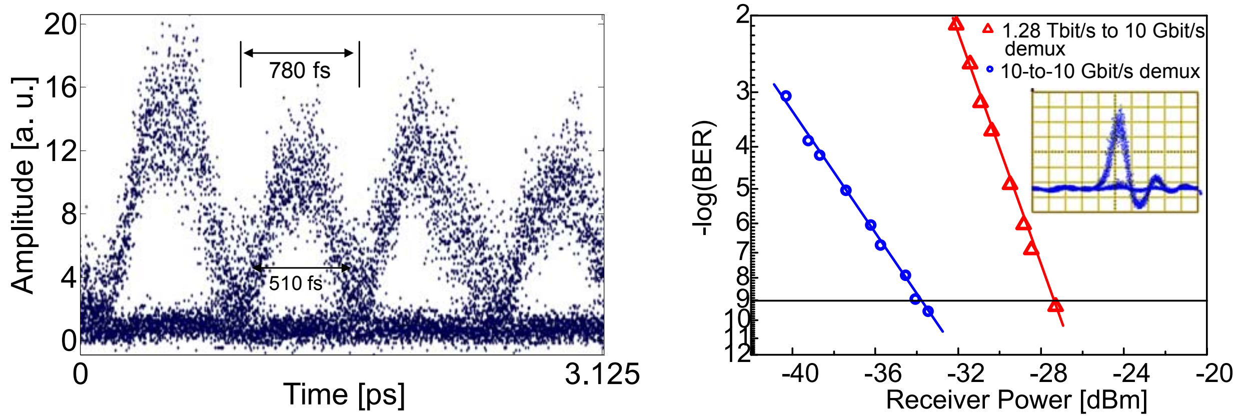

Figure 3. (Left) Clear eye-diagram from the Si-based optical sampling. (Right) BER performance of 1.28 Tbit/s-to-10 Gbit/s demultiplexing.

5. Conclusion

For the first time, we have demonstrated Tbit/s all-optical signal processing with a pure silicon nano-engineered waveguide. We have experimentally demonstrated a fourwave mixing based ultra-fast optical switching system with a Si nanowire, enabling successful optical waveform sampling and error-free demultiplexing both for 640 Gbit/s and 1.28 Tbit/s serial data signals. These experimental results, the high resolution sampling and the fastest silicon photonic optical signal processing, indicate a great potential of silicon nanowire based ultra-fast optical signal processing.

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